N73 15029

NASA TECHNICAL MEMORANDUM

NASA TM X-68173

NASA TM X-68173

OPTIMIZATION OF ENGINES FOR A COMMERCIAL MACH 0.85 TRANSPORT USING ADVANCED TURBINE COOLING METHODS

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November, 1972

E-7212

ABSTRACT

A parametric study was made of a group of separate-flow-turbofan engines for use in advanced technology airplanes designed for a cruise Mach number of 0.85 at 40 000 feet. The three-engined airplanes were sized to carry 200 passengers 3000 nautical miles. Supercritical aerodynamics were assumed. Film-cooled turbines were used and sea-level-static turbine-rotor-inlet temperature was always 2600° F. The optimum cycle depends on the noise goal assumed. Without a noise goal the best fan pressure ratio (FPR) is about 1.90. At noise goals of FAR 36, -10EPNdB, and -20EPNdB, the best FPR's are 1.85, 1.76, and 1.70, respectively, at cruise. The take-off FPR's are progressively less than the cruise value as the noise goal approaches -20EPNdB. The penalties in take-off gross weight incurred were 8.5, 19, and 64 percent at goals of FAR 36, -10EPNdB, and -20EPNdB, respectively.

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SUMMARY

A parametric study was made of a group of separate-flow-turbofan engines for use in advanced technology airplanes designed for a cruise speed of Mach 0.85 at 40 000 feet. The three-engined airplanes were sized to carry 200 passengers 3000 nautical miles. Cruise lift-drag ratios compatible with a supercritical wing were assumed. Fan pressure ratio was varied from 1.5 to 1.9 at cruise. Bypass ratio was varied from 1.0 to 15.0. Compressor pressure ratio was held at 15. The $T_{4\text{-sls}}$ was fixed at 2600° F and the best T_4 at cruise was found. Full coverage film cooling was used in the turbine. Engine weight varied with all major engine cycle parameters. Combined jet and machinery noise in EPNdB were calculated for all the engines at the sideline (lift-off) measuring station. The takeoff and approach conditions were considered also as specified in FAR, part 36.

It was found that the optimum FPR_{cr} ranged from 1.8 to 1.9 (when FAR noise goals were observed) to about 1.70 at a noise goal of FAR -20EPNdB. The penalty in TOGW to meet the FAR 36 noise goal was about 8.5 percent and FAR 36 minus 10EPNdB resulted in a 19 percent penalty. To meet FAR 36 minus 20EPNdB required about a 64 percent penalty. Noise goals as low as FAR 36 minus 20EPNdB were difficult to meet. In some cases they could not be met at all using only the 20PNdB of fan machinery noise suppression allowed in this study. In other cases the penalty was very large.

INTRODUCTION

The supercritical wing proposed by Whitcomb (ref. 1) offers the potential for delaying the transonic drag rise experienced by present day subsonic jet transports as their flight speed approaches Mach 1.0. Transports using this wing could cruise at the same speed as today's transports with less drag or they could cruise at somewhat higher speeds with little or no penalty in lift-drag ratio (L/D).

Previous studies (refs. 2 and 3) have been made to define the optimum engine design parameters for a Mach 0.98 advanced technology transport. In reference 2, turbine-rotor-inlet temperature (T_4) was allowed to vary assuming convection cooling for the turbine. In reference 3, very low noise goals were assumed to determine the need and direction for advanced noise suppression research. In reference 4, cruise Mach numbers from 0.90 to 0.98 were studied at one $T_{4\text{-sls}}$. In reference 5, an advanced turbine cooling method was investigated at Mach 0.98 to determine the benefits of higher T_4. The purpose of this study was to find the optimum cycle parameters when the cruise Mach numbers is reduced to 0.85 and the penalties associated with various noise goals.

Based on the results of references 2 through 5, the scope of this study was narrowed. The $T_{4\text{-sls}}$ was fixed at 2600° F and full-coverage film cooling was assumed for the turbine. Only one stage fans were considered because it was felt that the optimum fan pressure ratio (FPR) would be low enough to assure good performance from a one stage fan. The design compressor pressure ratio (CPR) was fixed at a value of 15. This would be an advanced technology single spool compressor and would aid the engines in reaching the optimum overall pressure ratios (OPR) of 25 to 30. Unlike references 2 through 5, specific fuel consumption (SFC) and net thrust (FN) penalties were included as a function of fan machinery noise suppression. The maximum attainable suppression considered was 20PNdB. The weight penalty due to suppression was more severe than in the other studies also. These changes reflect the results obtained from the ATT study contracts.

The range was fixed at 3000 nautical miles and the payload was held at 40 000 pounds (200 passengers). As engine design varied, the changes in engine weight, drag, and fuel requirements caused the TOGW to vary. The T_4 at cruise was optimized at each FPR and noise goal considered. However, cruise T_4 was never allowed to exceed takeoff T_4 - 200° F. This restraint assured an adequate thrust margin for acceleration, climb up to cruise, and for hot day performance.

Climb and letdown fuel weights were considered to be a linear function of TOGW. A nominal value of cruise L/D was selected from reference 4 at a cruise Mach number of 0.85. As engine pod size changed from the reference size, airplane cruise L/D was adjusted. It was assumed that wave drag changes could be largely ignored at this Mach number.

As in references 4 and 5, a component-matching computer program was used to do the off-design calculations such as at takeoff and during second segment climb. The jet noise was calculated by the SAE standard method of references 6 and 7 (assuming two separate streams). The machinery noise was considered to be a function of FPR, distance, and thrust. The jet and machinery noise were added to get the total noise at any point. Below a relative jet velocity of 1000 feet per second, jet noise was assumed to vary as V^8.

SYMBOLS

BPR	bypass ratio
bleed	total cooling bleed for turbines, fraction of compressor exit air
C_L	lift coefficient
C_s	speed of sound (n mi/hr) knots
D	drag, lb
FA	fuel to air ratio
FN	net thrust, lb
FPR	fan pressure ratio
ΔH_{AB}	change in enthalpy between stations A and B, Btu/lb
L	lift, lb
M	Mach number
OEW	operating empty weight, lb
OPR	overall fan and compressor pressure ratio

P	total pressure, lb/ft^2
R	range, n mi
sfc	specific fuel consumption (lb fuel/hr)/lb, thrust
T	total temperature, $^{\circ}F$
TOGW	takeoff gross weight, lb
$V_{fan\text{-}tip}$	sea-level-static fan tip speed, ft/sec
Wa	total airflow per engine, lb/sec
Wend-cr	airplane gross weight at the end of cruise, lb
Wstart-cr	airplane gross weight at the start of cruise, lb
δ	pressure parameter, P/2116
θ	temperature parameter, (T + 460)/519

Subscripts:

cr	cruise
sls	sea-level-static
1	fan face station
2	fan discharge station
3	inner compressor discharge station
4	turbine-rotor-inlet station
5	high pressure turbine exit station
6	low pressure turbine exit station

METHOD OF ANALYSIS

Selection of Reference TOGW and Airframe Weight

As in references 2 to 5 it was decided to select a reference airframe with which to match the various parametric engines. Range was initially calculated by the following equations

$$R = 350 + \frac{L/D_{cr}\, M_{cr}\, C_s}{sfc} \ln \frac{W\ start\ cr}{W\ end\ cr}$$

The 350 term represents the climb range, 200 n miles plus the letdown range, 150 n miles. The other terms on the right side of the equation represent the range for a Breguet cruise.

After an iteration described in references 2 to 4, the reference airplane was selected. It had a TOGW of 386 000 pounds, a payload of 60 000 pounds, and a range of 3000 n miles. The range was held fixed at this value for this study, however, the payload was reduced to 40 000 pounds. This reduced the reference TOGW below 386 000 pounds. This level of payload is more in line with the results of a recent NASA contract which was aimed at studying advanced technology transports. TOGW therefore, became the figure of merit in this report. According to reference 8, airframe weight will remain nearly a constant fraction of TOGW over a considerable range of TOGW when the size of large subsonic transports is scaled up or down. However, if the fuselage is held constant (as it was in this study) the fraction will change slightly as shown in figure 1. Note that this curve is only good for TOGW's from 200 000 to 500 000 pounds. The reason the fuselage was fixed was because the payload was fixed at 40 000 pounds (200 passengers at 200 pounds each). M_{cr} was selected as 0.85 and cruise was always started at 40 000 feet. Cruise L/D will be discussed later. Fuel for climb and letdown was estimated by the following equations.

$$\text{Fuel climb} = \frac{\text{TOGW}}{386\ 000} \times 20\ 000 \text{ pounds}$$

$$\text{Fuel letdown} = \frac{\text{TOGW}}{386\ 000} \times 2000 \text{ pounds}$$

The 386 000 pounds is the TOGW of the original reference airplane and the 20 000 and 2000 pounds are the fuel assumed for climb and letdown of that airplane. The reserve fuel was always assumed to be 18 percent of the total fuel load.

A sketch of the study airplane is shown in figure 2. In the sketch, the engines are installed in the rear of the airplane. Other options such as having one in the tail and one under each wing may offer certain advantages. However, their location would have no impact on the way this study was done or its results. A sketch of a typical high BPR, separate-flow turbofan engine is shown in figure 3. Note the acoustic lining in the inlet and duct walls for the reduction of fan machinery noise. In addition, inlet and duct splitter rings are shown with sound deadening material. Different amounts of treatment are required to achieve different amounts of suppression. The weight and amount of these materials needed will be discussed later.

Lift-Drag Ratio

The L/D used for the reference airplane in this study was 20.0. This value was obtained through consideration of present day transports, test data for advanced transports as discussed in reference 4, and an extrapolation of the L/D against Mach number curve in reference 4. This value of L/D includes the drag of three, 80-inch-diameter nacelles. The drag of one of the 80-inch engine nacelles is shown as a circled reference point on figure 4. The L/D ratio was adjusted by means of the curve shown in this figure as the engine nacelle diameter varied from 80 inches. The nacelle drag curve of figure 4 agrees with those in use by the engine and airframe manufacturers. By far the greatest part of this nacelle drag is due to friction. It is assumed that when nacelle size is changed, changes in wave drag can be ignored at this Mach number. If the reference L/D was somewhat lower than 20.0, the airplane TOGW would be greater. However, L/D would have to be reduced by a large amount to have any effect on the optimum cycle except for design airflow (Wa).

Engines

Cycle calculations were made for two-spool separate-flow turbofan engines in this study. Only three cruise fan pressure ratios were considered, 1.50, 1.70, and 1.90. This range of FPR was chosen because it was felt that the optimum FPR would be in this range for airplanes designed to cruise at Mach 0.85. Single-stage fans were used because (1) they can achieve the FPR desired, (2) more is known about their noise characteristics, and (3) the trends resulting from this study were bound to have a discontinuity at the point a two-stage fan was used. As discussed in reference 4, 15PNdB of machinery noise suppression may be available today and 20PNdB may be available in a few years. 20PNdB of suppression from stuffing was the maximum considered in this study.

Cruise bypass ratios from 0.5 to 15 and overall pressure ratios from 22.5 to 28.5 were considered. The design cruise pressure ratio of the compressor was never varied from 15. This was meant to represent an advanced compressor driven by only one turbine stage. The sea-level-static T_4 was fixed at 2600° F for standard day operation. This level of $T_{4\text{-sls}}$ represents an advance over today's levels and should be near optimum as discussed in reference 5. The engines were sized at cruise for several levels of cruise $T_{4\text{-cr}}$. The maximum cruise T_4 ever used was the $T_{4\text{-sls}}$ - 200° F, or therefore, 2400° F. This minimum of 200° F delta insured reasonable thrust margins during climb, reasonable time up to cruise, and adequate hot day performance. The best $T_{4\text{-cr}}$ would normally be the highest value, 2400° F. But this was not always the case when all the tradeoffs caused by noise and takeoff thrust constraints were imposed. These constraints will be discussed later. Let it suffice at this point to say that several values of T_{4-cr} had to be considered to find the optimum value.

As in reference 5, no turbine cooling schedule was assumed in this report. Instead, an advanced cooling scheme - full coverage film - was assumed and the cooling for each stator and rotor was calculated at take-off levels of T_4. In order to do this, the number of stages in the turbine had to be established. It was assumed that the high-pressure turbine consisted of only one stage. The cooling for the stator was not calculated since our cycle calculations deal with T_4, rotor-inlet temperature. Any stator cooling airflow is included in the combustor airflow and was not calculated. The number of low-pressure turbine stages can be as few as one at low BPR's or as great as 10 or more at high BPR's. The following equation was derived to calculate the number of low-pressure turbine stages necessary for any engine.

$$\text{Number of stages} = 9600 \frac{(1 + \text{BPR})(P_6/P_1)(\Delta H_{6,5})}{\left[1 + FA_4(1 - \text{bleed})\right] (V^2)_{\text{fan-tip}} \sqrt{T_6/T_1}}$$

Several assumptions are necessary before this equation can be derived. One of these is a schedule of corrected fan-tip speed against FPR. The schedule used in this study is shown in figure 5. The curve is a linear approximation tangent to the curve in reference 9 for a fan blade loading of 0.3 at a $V_{\text{fan-tip}}$ of 1900 ft/sec. (A complete explanation of the turbine cooling calculations, number of low-pressure turbine stages calculations, and the assumptions are given in appendix A of reference 5.) This procedure obviously is not exact, but it gives good results when compared against more elaborate ways of estimating the number of stages.

Knowing the number of stages and the delta H and delta T across each stage, the cooling bleed could be calculated for each stage. The cooling was based on laboratory tests of full-coverage film cooled vanes tested in Allison's high temperature cascade rig. The blades were of advanced design using advanced fabrication techniques. The bulk metal temperature of the blade was fixed at 1650° F for the rotors and at 2000° F for the vanes.

The entire process for calculating bleed and the appropriate references are covered in reference 5.

All the engines in this study were designed at cruise and thus operated off-design at takeoff. All off-design calculations were done with the aid of a component-matching computer program, ref. 10. This program uses component maps in the matching procedure. During component-matching procedures at off-design, nozzle exhaust areas were assumed fixed at their design value.

At each cruise design point, the component efficiencies, pressure losses, coefficients, etc., were as follows:

Compressor adiabatic efficiency.	0.86
Combustor efficiency	0.99
Inner turbine adiabatic efficiency	0.89
Outer turbine adiabatic efficiency	0.88
Inlet pressure recovery	0.98
Pressure ratio across combustor	0.96
Total duct pressure ratio from fan discharge to nozzle	0.94
Total core pressure ratio from low pressure turbine discharge to nozzle	0.98
Exhaust nozzle thrust coefficient (both streams).	0.98

Fan design adiabatic efficiency was allowed to vary with design FPR and thus fan-tip speed. The efficiency was 0.856, 0.838, 0.824 at design FPR's of 1.5, 1.7, and 1.9, respectively.

Installed engine weight and dimensions were allowed to vary with changes in engine sea-level-static parameters as described by reference 11. This correlation includes the effect of year of first flight. The year was chosen at 1973 in this study. This yields bare engine thrust to weight ratios just slightly better than with current engines used on the first generation wide body jets.

In addition to the bare engine weight, each engine was assumed to have an installation weight of 3.13 times the corrected total airflow at takeoff. This included such items as inlet, nacelle, and nozzle. This installation weight is based on empirical data for existing high-BPR engines used in the wide body commercial transports. The weight due to suppression of fan noise will be discussed later.

In references 2 through 5 the only thrust to airplane weight (FN/TOGW) limit observed was a minimum value of 0.24 dictated by engine out requirements. To make sure that the airplanes were quiet enough at the takeoff noise measuring station and to account for the differences in lapse rate with BPR, a different FN/TOGW limit was observed in this study.

Figure 6(a) is a plot of thrust lapse against BPR_{cr}. The thrust lapse in this case is the ratio of FN at Mach 0.3 and 1500 feet to the FN at sea-level-static. It was found that because of this thrust lapse the $(FN/TOGW)_{sls}$ required to reach Mach 0.3, 1500 feet, at a range 3.5 nautical miles from start of takeoff roll varied according to the schedule shown in figure 6(b). The thrust lapse and thus the FN/TOGW schedules shown in figure 6 were found to be almost independent of FPR_{cr} within the range studied. Thus only one schedule resulted.

Cost Estimation

Direct operating cost (DOC) was computed for the optimum engines at each noise goal using the 1967 ATA domestic formula. Because of uncertainties in costs at this preliminary stage, only relative DOC has any merit. In this study, airframes were assumed to cost $72 per pound (based on current airplanes). Acoustic suppression materials for turbomachinery noise was assumed to cost the same per pound as the airframe. Engine price was assumed to be a function of sea-level-static corrected airflow and was computed as follows

$$C_{eng} = 1.2\times10^{6}\left[\frac{\left(Wa\sqrt{\theta_1/\delta_1}\right)_{sls}}{1300}\right]^{0.35}$$

This cost is based on empirical data adjusted to reflect the typical cost of a high-BPR turbofan such as those used to power the new wide-body trijets.

Noise Calculations and Constraints

Noise calculations and estimates were made for two measuring points both of which are specified in Federal Air Regulation, Part 36 (FAR 36). They were:

(1) Sideline noise measured on the ground at an angle of maximum noise (20^{o} was assumed between the airplane and the observer on the ground) after lift-off on a 0.25-nautical mile sideline for these three-engine airplanes. The point of maximum noise would be after the aircraft reached an altitude where ground attenuation and engine masking was greatly diminished. The aircraft Mach number was assumed to be 0.30 and the altitude was 500 feet.

(2) Takeoff noise at a point 3.5 nautical miles from the start of takeoff roll on the extended runway centerline. Since the airplanes in this study were always at an altitude of 1500 feet at this point and since the power was allowed to be reduced, this noise was always substantially less than the sideline noise. Thus, it was not necessary to make actual calculations at this point even though the takeoff noise goal is 2 to 3 EPNdb less than the sideline goal at any given TOGW of interest in this study.

A third measurement point specified by this regulation should be approach noise. This normally would be measured with the aircraft at an altitude of 370 feet directly under the aircraft flight path and one nautical mile from the runway threshold. This calculation was not made in this study since it was found in reference 5 that this condition was no more severe than sideline. Also there are a great many things that could be done during approach to lessen the noise if it became unacceptable. Some of these are (1) increase the glide slope, (2) increase the landing speed by reducing the flap setting and power, (3) choke the inlet.

For airplanes of interest in this study FAR Part 36 specifies a noise goal of approximately 106EPNdB at sideline and approach and 103.5EPNdb at takeoff conditions. The Mach number assumed for sideline and takeoff noise points was 0.30. At approach the Mach number was 0.203.

Total perceived noise has two components; jet noise from two jet streams and for turbomachinery noise. The jet noise was calculated by the standard methods described by the Society of Automotive Engineers in references 6 and 7. Fan turbomachinery noise was considered to be a function of FPR as shown in figure 7 as well as thrust and distance. This curve is based on reference 12 and is really a composite curve. It represents a low speed fan with few (if any) multiple pure tones (MPT's) at a FPR of 1.5, and a high-speed fan with MPT's at a FPR of 1.9. The band of accuracy on this curve is expected to be ±2PNdB. A spectral distribution for fan machinery noise was assumed based on reference 13 and shown in reference 5. The total perceived noise was obtained by adding the machinery noise and jet noise by octaves as described in reference 6 for the addition of two jet stream noise sources. The basic noise calculations in this report were made in terms of PNdB. However, the results are given in terms of EPNdB. This conversion can be accomplished by subtracting 5PNdB from approach noise (approach was not calculated in this study), nothing from sideline noise, and 1PNdB from the takeoff noise. This method is approximate and independent on the time history of the noise and its pure tones. The time history and pure tones of all the engines were assumed to be the same since the takeoff and approach velocities and altitudes were specified. This result agrees with the methods used by industry in a preliminary study like this.

In this study, attention was concentrated on designing cycles that would minimize the TOGW for a given noise goal. Up to 20PNdB of fan machinery noise suppression (stuffing) was assumed where necessary. It was assumed that as suppression increased, losses in FN and sfc would occur as shown in figure 8(a). This is based on a composite of results from the ATT contracts. The weight of acoustic treatment was accounted for by adding weight to the engines according to a schedule which related weight penalty to amount of suppression. This schedule is shown in figure 8(b). This weight penalty is much more severe than in reference 5 but is based again on the ATT contract results. The actual configuration of the suppression ranged from linings only at 5PNdB suppression to linings plus three inlet and two duct splitter rings at 20PNdB of suppression. The weight was scaled with engine diameter for other size engines.

At each FPR_{cr} and T_{4-cr} considered, the effects of BPR_{cr} and TOGW were calculated. "Thumbprint" plots were then drawn displaying contours of constant TOGW as functions of BPR_{cr} and fan machinery noise suppression. Sideline total noise constraints were laid over this thumbprint and a group of optimum engines were picked off. These engines resulted in the minimum TOGW for any noise level assumed. This resulted in not only the optimum BPR_{cr} but also the optimum amount of suppression. An example of this type of plots is shown in figure 9. This figure happens to be for a FPR_{cr} of 1.90 and a T_{4-cr} of 2400° F. This type of figure was constructed for each FPR_{cr} at T_{4-cr} values of 2400°, 2300°, and 2200° F.

The locus of optimum engines was plotted again as TOGW against sideline noise. An example of this type of plot is shown in figure 10. This figure is for a FPR_{cr} of 1.9. The delta $T_4 = 200^{\circ}$ F line is from figure 9. The other two lines are from plots like figure 9 where T_{4-cr} was 2300° and 2200° F. Since this is only for a FPR of 1.9, two other plots like figure 10 are necessary to completely show all the optimum engines at three levels of FPR and three levels of T_{4-cr}.

The three points on the curves show where the proper $(FN/TOGW)_{sls}$ occurs so that the airplane will reach an altitude of 1500 feet and Mach 0.30 at the 3.5 nautical mile noise measuring point. Thus the dashed line through the three points represents the lowest TOGW that can be obtained for any sideline noise level for engines with a FPR_{cr} of 1.90. Two other such plots were made for $FPR's_{cr}$ of 1.70 and 1.50. From these curves the best FPR_{cr} can be chosen at any noise level.

RESULTS AND DISCUSSION

Comparison in Terms of TOGW

The best TOGW at each FPR is plotted against FPR_{cr} for lines of constant sideline noise in figure 11. This figure is a result of cross plotting the dashed line in figure 10 and two figures like figure 10 but at FPR_{cr} of 1.5 and 1.7. If there was no noise goal the best FPR_{cr} (within the range studied) would be about 1.90 at a TOGW of 210 000 pounds. This will be the reference point used to describe penalties.

When a noise goal of FAR 36 is applied, the TOGW increases 8.5 percent to 228 000 pounds at a FPR_{cr} of 1.85. Lowering the noise goal below FAR 36 increases the TOGW still farther. At FAR 36 minus 5EPNdB the minimum TOGW is 233 000 pounds at a FPR_{cr} of 1.82. At FAR 36 minus 10EPNdB the TOGW increases to 250 000 pounds, a penalty of 19.0 percent at a FPR_{cr} of 1.76. If the noise goal sought is FAR 36 minus 15EPNdB, the TOGW is 287 000 pounds at a FPR_{cr} of 1.73. This is a penalty of 36.6 percent. A noise goal of FAR 36 minus 20EPNdB could be met if desired but the TOGW penalty would be even more prohibitive. Also, the entire process of picking the best engine is becoming more delicate. From figure 11 the minimum gross weight occurs at a FPR_{cr} of 1.70. This is a TOGW of 345 000 pounds and a penalty of 64 percent. Even more important though is the restrictive implications of the curve. If a FPR_{cr} much greater than 1.70 is chosen it appears doubtful that the noise goal can be met at all with the maximum of 20PNdB fan machinery noise suppression assumed in this study. If a FPR_{cr} much less than 1.7 was chosen, the noise goal could be met but the TOGW increases at an alarming rate. The dashed line in this figure and following figures will mark the locus of optimum engines at each noise goal as defined by minimum TOGW.

Figure 12 has nine parts. The various parts of the figure define some of the more important design characteristics of the best engines at each FPR_{cr} and the final optimum engines at each noise goal.

Optimum Cycle Parameters

The optimum BPR_{cr} at each FPR_{cr} for the various noise goals is shown in figure 12(a). At any noise goal a decrease in FPR_{cr} dictates an increase in BPR_{cr}. This is necessary in order to keep the low pressure turbine work load fairly constant so that the primary jet noise can be maintained at some level below the noise goal. As lower noise goals are assumed, the BPR_{cr} must increase in order to further lower the primary jet noise. These trends are normal. However, some caution should be used in accepting these BPR_{cr} values just as they are plotted. One thing that was not evaluated in depth is the effect of power extraction from the gas generator core. This power extraction is needed to drive various accessories such as air-conditioning for the passenger cabin. For this size airplane the power extraction could amount to 200 to 500 hp from each engine. Taking horsepower from the core lowers the primary jet velocity and would then allow a slightly lower cruise BPR to be selected. The final BPR_{cr} selection would be dependent on such factors as these but would be very close to those reported in this report. The effect of this power extraction was not included in the basic calculation because the proper level was not known. Also, since the BPR's$_{cr}$ are all above optimum (for best performance without noise goals) lowering the BPR_{cr} can only help decrease the TOGW. Once the proper power extraction is determined, all that remains is to take the optimum FPR_{cr} and select the proper BPR_{cr} to get the primary jet noise down to the level necessary. The range of optimum BPR_{cr} was from 5.3 at a noise goal of FAR 36 to 10.1 at a noise goal of FAR 36 minus 20EPNdB.

As was shown in figure 9 there is an optimum schedule of BPR_{cr} and suppression. Figure 12(a) showed the BPR_{cr} part and figure 12(b) shows the optimum suppression that goes with it. Since the penalties in weight, FN and sfc were pretty large for additional suppression, the optimum levels of suppression tended to remain as low as possible. The maximum level of suppression (20PNdB) was chosen only in a couple of instances at noise levels of FAR 36 minus 15 and 20EPNdB. This desire to minimize suppression forced the jet noise floor farther below the noise goal than in references 2 to 5. The optimum suppression ranged from only 4PNdB at FAR 36 to 20PNdB at the FAR 36 minus 20EPNdB noise goal.

Because the relationship of $T_{4\text{-sls}}$ and $T_{4\text{-cr}}$ varies (as will be shown shortly) from one engine to another, no general rule of thumb can adequately explain where the engine compressors and fan will match at sea-level-static compared to the design point at cruise. For this reason figures 12(c) and (d) were drawn.

Figure 12(c) shows the relationship of FPR_{sls} to FPR_{cr} at each FPR_{cr} for each noise goal. For example, to meet a noise goal of FAR 36 minus 20EPNdB with a design FPR_{cr} of 1.7 would require the fan to operate at a FPR of only 1.51 at sea-level-static. This apparent mismatch is a result of optimizing the engine for two different conditions at the same time. The low FPR_{sls} is desired because of fan machinery noise considerations and the higher FPR_{cr} is a result of trying to get better performance at cruise. Note that as the noise goal is relaxed to FAR 36, the optimum FPR_{cr} is 1.85 which results in an optimum FPR_{sls} of 1.84. The mismatch has disappeared since the noise goal was not as strict.

A close check of figure 12(a) and (d) will show that the BPR does not change very much between sea-level-static and cruise. The optimum BPR_{cr} at a noise goal of FAR 36 (from fig. 12(a)) is 5.3 and it is 5.2 at sea-level-static from figure 12(d). At a noise goal of FAR 36 minus 20EPNdB, the optimum BPR at cruise and sea-level-static is 10.1 and 10.2, respectively. This relationship is a result of the component maps used but probably would hold true for any realistic component maps.

The maximum engine diameter in inches is shown against FPR_{cr} for the various noise goals in figure 12(e). An approximate maximum allowable diameter band is shown on the curve also. This band has been determined by industry and is set by the technology inhand today. Notice that all the engines of real interest fall below the band except the optimum engine of FAR 36 minus 20EPNdB. That engine is only slightly into the bottom of the band. In general, diameter tends to increase as either BPR_{cr} increases or FPR_{cr} decreases. This is caused, in part, by the cruise sizing criteria used in this study. Thus, since a nearly constant cruise

FN is required, the faster lapse rate of high BPR and/or low FPR engines require a larger engine airflow at cruise. This is shown in figure 12(f) where corrected airflow $(Wa)_{sls}$ is shown. Since corrected Wa is also an indicator of engine size, the shape and slope of these curves follow those of the maximum diameter curve above. The optimum engine airflow ranges from 670 pounds per second at a noise goal of FAR 36 to 1435 pounds per second at a noise goal of FAR 36 minus 20EPNdB.

As was explained in the Method of Analysis during the discussion of figure 10, the T_{4-cr} was not a constant value. It varied from a preset maximum of 2400° F to at times less than 2200° F. Figure 12(g) shows the delta T_4 at a cruise for the engines at each noise goal. Where

$$T_{4-cr} = 2600^{\circ}\ \mathrm{F} - \Delta T_4$$

These delta T_4's are the result of trying to find the best match point at cruise for performance, the best match point at takeoff for noise, and still satisfy the FN/TOGW constraints. The optimum delta T_4 at cruise ranged from 390° to 205° F. The lower delta T_4 (higher actual T_4) were most desirable at low noise goal because it helped keep the engine weight down.

The engine weight is a function of many things as discussed in the Method of Analysis. The weight and drag of the engines has a bearing on determining the optimum cycle also. The bare engine weight per engine is shown in figure 12(h) for the engines at each noise goal. The shape and slope of the lines generally follow the curves for corrected airflow shown in figure 12(f). The minimum points for each noise goal occur close to the FPR_{cr} that is optimum from the TOGW standpoint. This indicates the strong influence that engine weight has on selecting the optimum cycle.

As a result of the desire to reach a Mach number of 0.30 and 1500 feet at the 3.5 nautical mile point, figure 6 was shown in the Method of Analysis. Figure 12(i) shows the actual (FN/TOGW) that was finally required of the engines at each noise goal. The values range from about 0.31 to over 0.33. These values are in the same range as for the 747 and DC-10 airplanes. If anything, the values reported here are a little higher than for those two airplanes. This is to be expected because some of the noise goals for ATT are lower than for the 747 or DC-10. Therefore, higher speed and/or higher altitude are desirable to aid in lowering the noise at takeoff after power cutback. Of course, the airplane used in this study has slightly better aerodynamics than a 747 or DC-10 also.

TRADEOFF OF DOC AGAINST NOISE

Due to lack of information on the cost of aircraft and engines at such a preliminary stage as this, the costs had to be estimated as discussed in the Method of Analysis. Because of the way the costs were estimated, the relative DOC trends follow the trends in TOGW pretty closely. (This was observed in ref. 5 also.) However, to get a better feel for what noise goals mean in terms of economic penalties, DOC was calculated for the optimum engine at each noise goal.

The relative DOC is shown in figure 13 against noise goal. FAR 36 was used as the reference point (relative DOC = 1.0) since all new aircraft must presently meet this goal anyway. To meet a noise goal of FAR 36 minus 5EPNdB costs about 2.5 percent in DOC according to figure 13. The penalty reaches 9 percent at FAR 36 minus 10EPNdB; 21.5 percent at FAR 36 minus 15EPNdB; and 41 percent at FAR 36 minus 20EPNdB. At this time no one is willing to say just what penalty is acceptable or unacceptable. This subject has led to much debate and will not be settled for some time to come. In this case, the relative DOC shows a penalty of 41 percent at FAR 36 minus 20EPNdB whereas, if just TOGW were considered, the penalty would be 56 percent relative to FAR 36. Which is the right answer is not perfectly clear but it is a fair bet that neither would be acceptable at that level of penalty.

One further observation is that the slope of the curve at FAR 36 indicates that just to reach this noise level there is some penalty. This fact is often overlooked since all the new airplanes are designed to meet FAR 36. Without this noise goal the engines on today's new airplanes would tend to have higher FPR's and lower BPR's. So where a penalty is referenced to can have an important impact on its relative merits.

Cycle Matching Results

For most commercial subsonic transports in operation today, it is not uncommon to refer to FPR and not say if it is a cruise or sea-level-static value. This is because the two values are quite often very close together. This is not always the case in this study where noise is such a driving influence. To demonstrate the point, figure 14 was plotted. This is a typical fan map with FPR plotted against fan airflow. The lines of constant efficiency were left off of the figure because they are not needed for this discussion.

Note that five optimum engines are going to be considered. These are the ones that would be picked off of figure 11 (the bucket point on each curve). As shown in figure 13, all of the engines were designed at the same relative point at cruise, 100 percent speed and airflow. When a noise goal of FAR 36 was met at takeoff the sea-level-static operating point of the fan (the square) is very close to the design point just as in todays engines. However, as the noise goals are lowered, the sea-level-static point moves to lower corrected speed, lower corrected flow, and lower FPR. Thus the desire to reduce FPR at takeoff (since fan machinery noise is a function of FPR) has a powerful effect on how the cycle will match and thus which cycle is chosen as optimum. At a noise goal of FAR 36 minus 20EPNdB, there is obviously a strain between the desire for high FPR (1.70) at cruise to give good performance and low FPR (1.51) at takeoff to help keep the machinery noise down.

Another result that is very interesting when contrasted to reference 5 is the trade between adding more suppression and changing the cycle. When the penalties were small for adding suppression (as assumed in ref. 5) the trade favored adding more suppression. Thus, at any noise goal, the cycle was adjusted only enough to make sure the jet floor was slightly below the goal. In this study, the weight penalties were more severe than in reference 5 and in addition, FN and sfc penalties were applied to the engines with suppression as previously discussed. The penalties were severe enough in this study to reverse the direction of the trade found in reference 5. Thus in this study it was usually more favorable to change the cycle some and add less suppression. As a result of this, the jet noise floor is well below the noise goal.

Thus it can be seen that suppression penalties can have a large effect on the trades to be made in an optimization study as well as the absolute answer. A study such as this should be used as a guide to the approximate penalties involved in reaching a certain noise goal. It can be used to identify the area of interest from the cycle point-of-view also. But to obtain an absolute answer to exactly what airplane, what engine, or how much suppression to meet a certain noise goal, a very detailed study would have to be done in the area shown to be of interest in this study.

CONCLUDING REMARKS

A parametric study was made of a group of separate-flow-exhaust turbofan engines for use in an advanced-technology transport designed to cruise at Mach 0.85. Initial cruise altitude was 40 000 feet, total range was 3000 nautical miles and the payload was 40 000 pounds (200 passengers). The airplane was assumed to have 3 engines of slightly advanced weight technology. An advanced turbine cooling scheme was assumed (full coverage film) and the cooling flow for each stage of the turbine was calculated. The sea-level-static turbine-rotor-inlet temperature on a standard day was fixed at 2600° F and the optimum cruise turbine-inlet-temperature was determined. Combined jet and fan machinery noise calculations were made for all the cycles at the 0.25 n mile sideline station specification FAR Part 36. The altitude and speed was adjusted at the 3.5 nautical mile measuring point (takeoff) so that the noise at this point could reasonably be assumed to be less than the sideline value after power cutback. The approach noise was not calculated because it can be controlled by aircraft procedures to a significant extent if it does try to dominate.

Fan pressure ratios (FPR) of 1.5, 1.7, and 1.9 were used at cruise. The cruise compressor pressure ratio was held at 15. Engine BPR and fan machinery noise suppression was optimized at each FPR to give the lowest TOGW at any noise goal. Noise goals as low as FAR 36 minus 20EPNdB were investigated. Suppression of fan machinery noise up to 20PNdB was considered available.

It was found that the TOGW of the optimum airplane was 210 000 pounds if no noise goal was forced on it. The optimum FPR_{cr} was 1.90 and the BPR_{cr} was 4.80. When a noise goal of FAR 36 (about 106EPNdB sideline) was applied, the TOGW increased by 8.5 percent above the reference level of 210 000 pounds. The optimum FPR_{cr} is reduced to 1.85, BPR_{cr} is 5.2, and the suppression of machinery noise is 4PNdB. These general trends continues such that the penalties in TOGW are 19 percent at a noise goal of FAR 36 minus 10EPNdB and 64 percent at a noise goal of FAR 36 minus 20EPNdB. The optimum FPR_{cr} has been reduced to 1.70 and the optimum BPR_{cr} has increased to 10.1 by this time. This trend to change FPR_{cr} and BPR_{cr} by such great amounts is caused by a desire to get the jet noise floor of the optimum engines substantially below the noise goal so that the suppression of machinery noise is a minimum. This situation is promoted by the large penalties in weight, sfc, and thrust that were a function of suppression in this study. These penalties are felt to be a realistic projection of advanced suppression techniques. If, however, the penalties associated with suppression can be further reduced, the penalties in TOGW associated with any noise goal will also be reduced.

The penalties shown in this report are, of course, based on a reference point of equal technology engines and airplanes. If the reference point had been a transport without a supercritical wing, using engines of today's technology (meaning heavier engines and lower temperature) the reference point would not have been so good. Then the penalties shown in this study, with respect to the new reference point, would have been reduced or in some cases appeared as an improvement. Thus, the penalties quoted can only be taken as absolute values when the reference point is as defined in this study.

If DOC is used to define the penalties, the percent change in DOC is just slightly less than the change in TOGW for the assumptions used in this study. Thus, either parameter yields equivalent conclusions.

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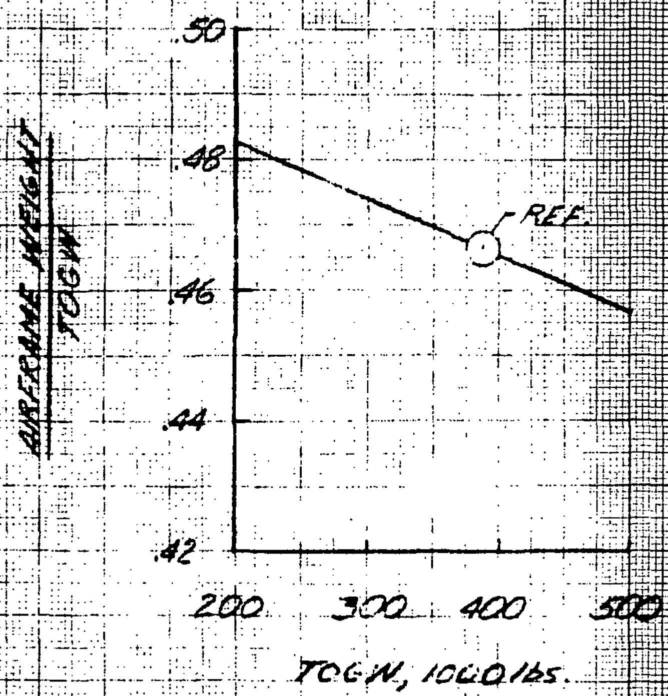


FIGURE 1. - AIRFRAME WEIGHT FRACTION
FUSELAGE DIMENSIONS FIXED,
TAKEOFF WINGLOADING FIXED.

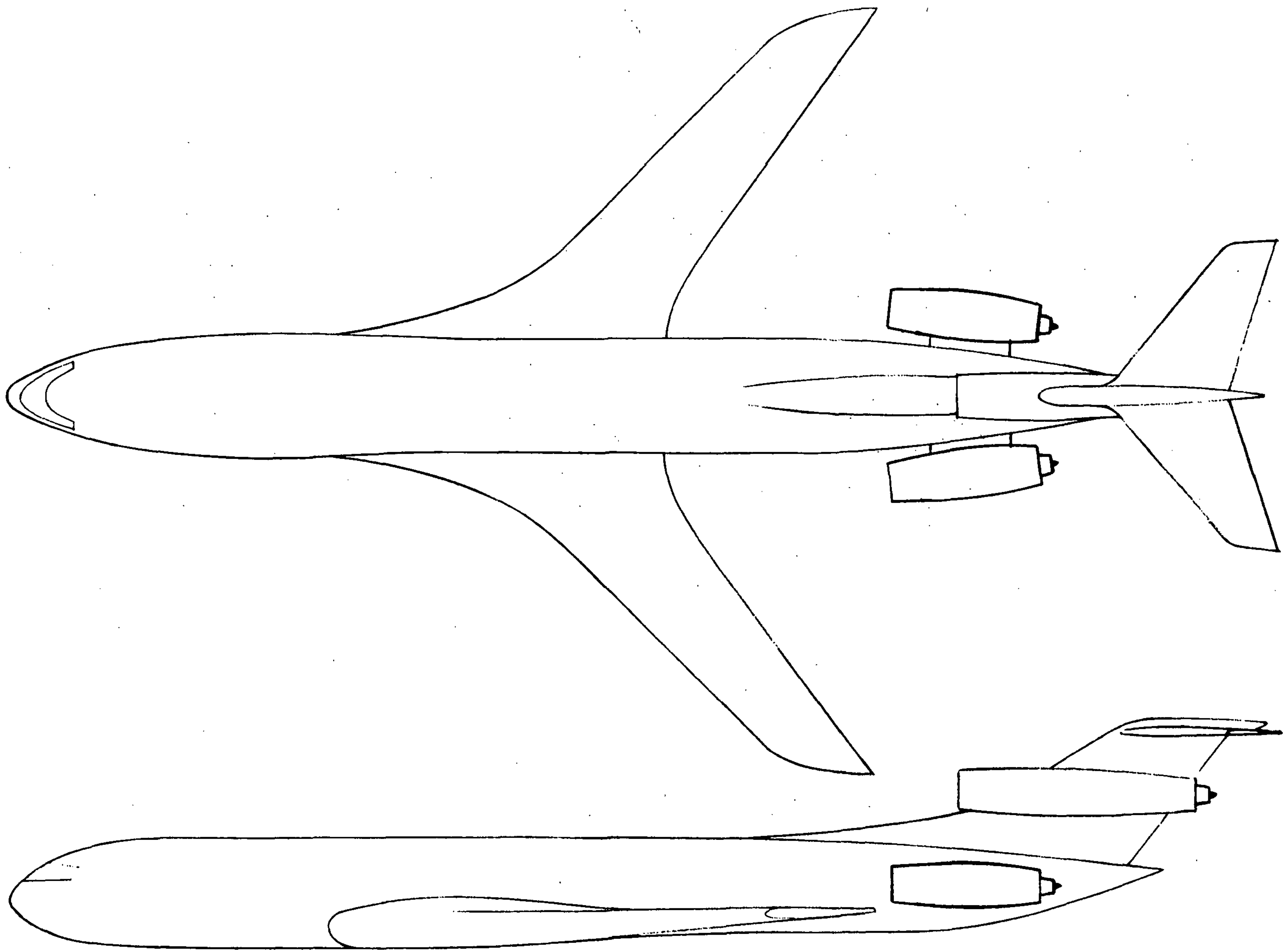


FIGURE 2.— SKETCH OF CONCEPTUAL ADVANCED TRI-JET TRANSPORT.

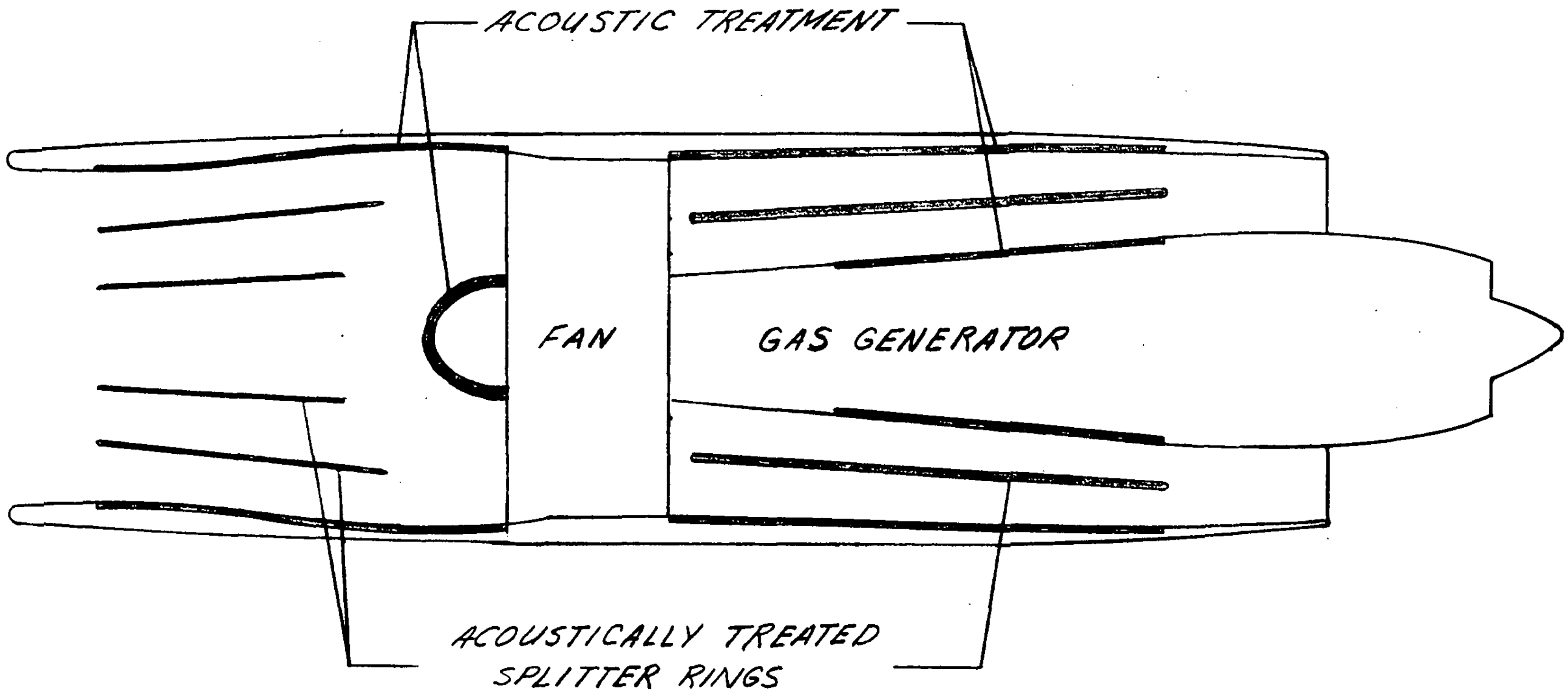


FIGURE 3.- SKETCH OF TURBOFAN ENGINE WITH ACOUSTIC TREATMENT

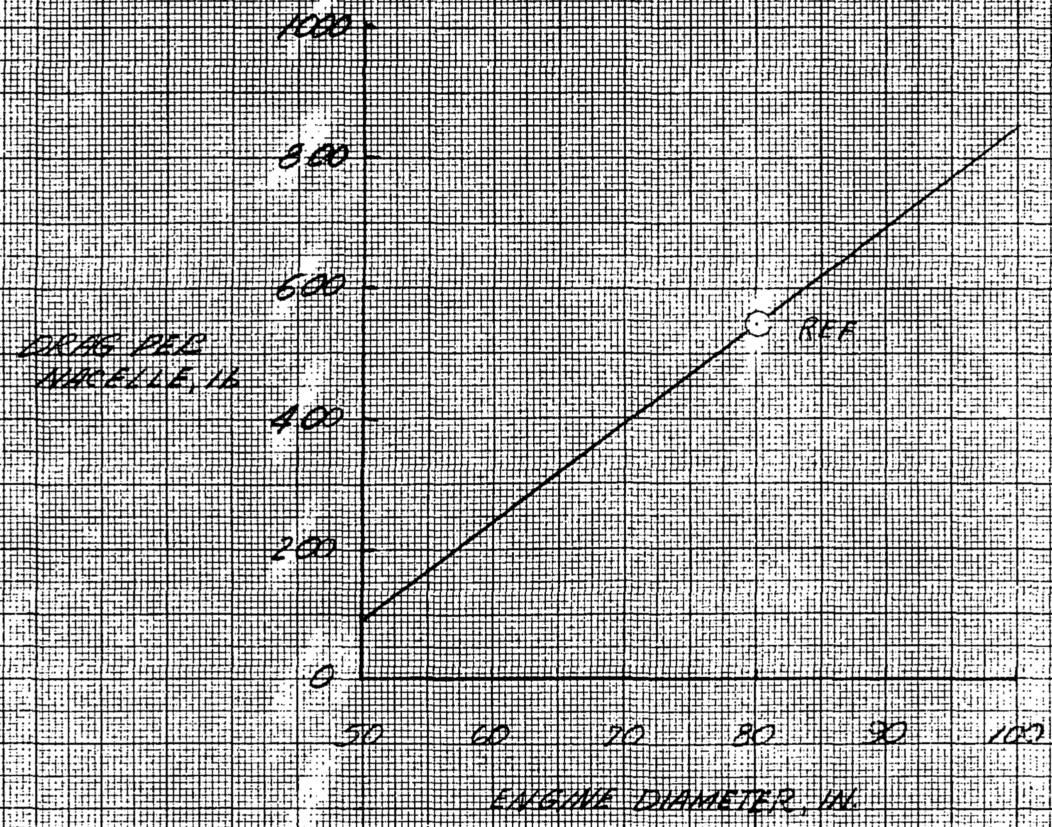


FIGURE 4. - NACELLE DRAG RELATED TO ENGINE MAXIMUM DIAMETER, CRUISE MN, 0.85.

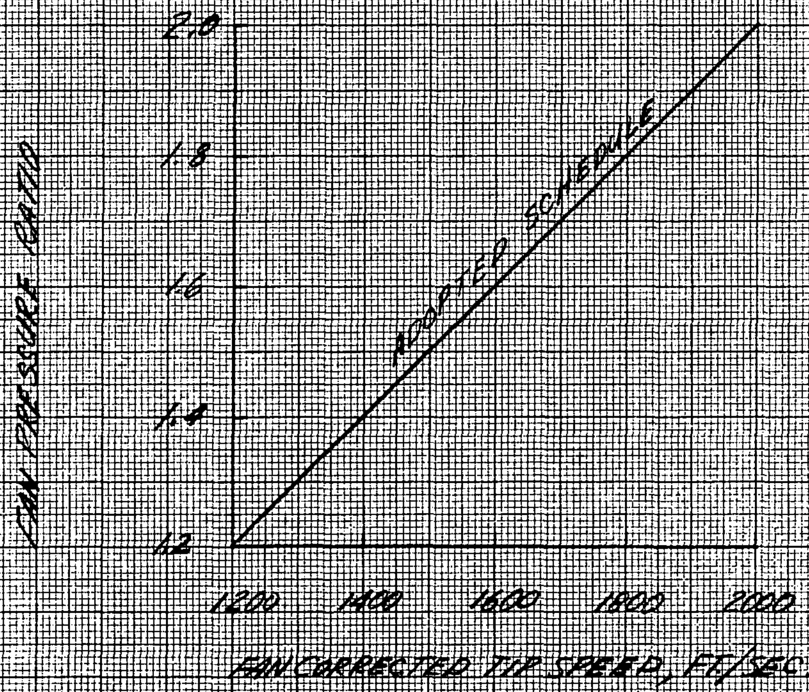
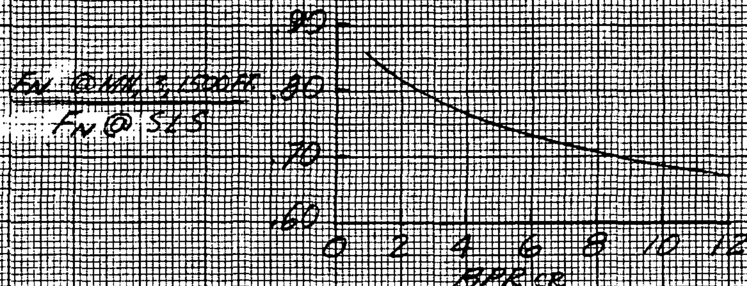
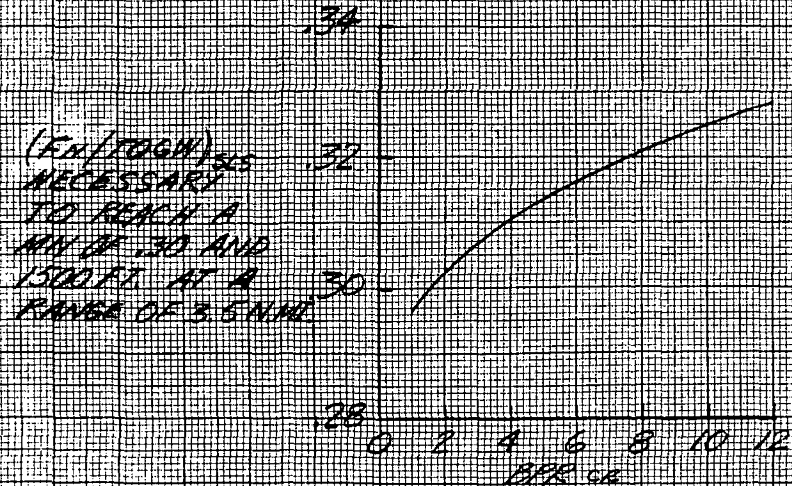


FIGURE 5. - FAN TIP SPEED FOR ONE STAGE FANS.



(a). THRUST LAPSE



(b). THRUST TO WEIGHT

FIGURE 6. - THRUST LAPSE VERSUS BPR CR AND THE RESULTING REQUIRED TAKEOFF THRUST TO GROSS WEIGHT RATIO SUCH THAT A ALTITUDE OF 1500 FEET AND MACH NUMBER OF 0.30 CAN BE ACHIEVED BY ALL AIRPLANES AT A RANGE OF 3.5 N.MI.

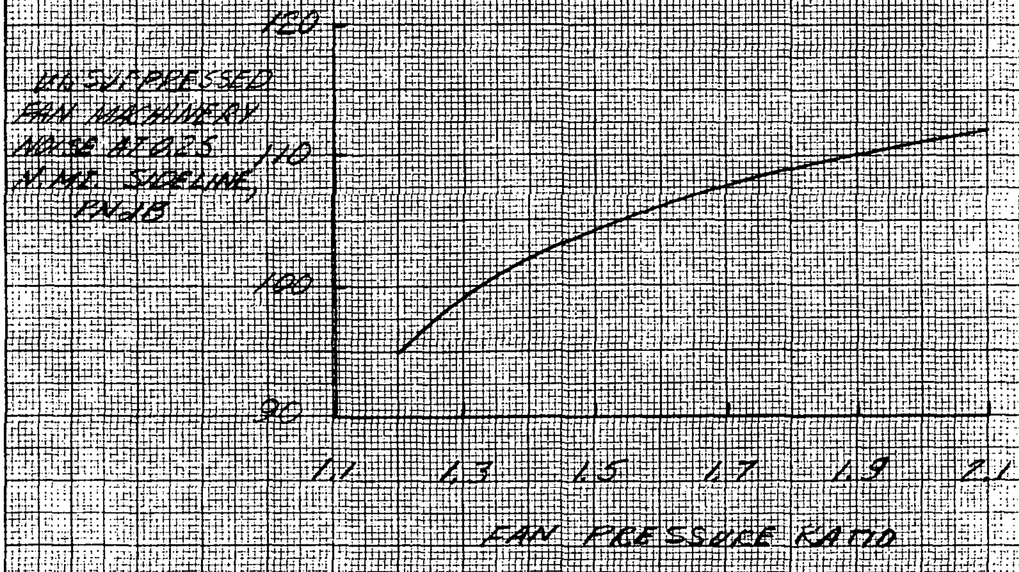


FIGURE 7.- FAN MACHINERY NOISE VERSUS FAN PRESSURE RATIO FOR SINGLE STAGE FANS, F_{N-SLS} = 114000 POUNDS.

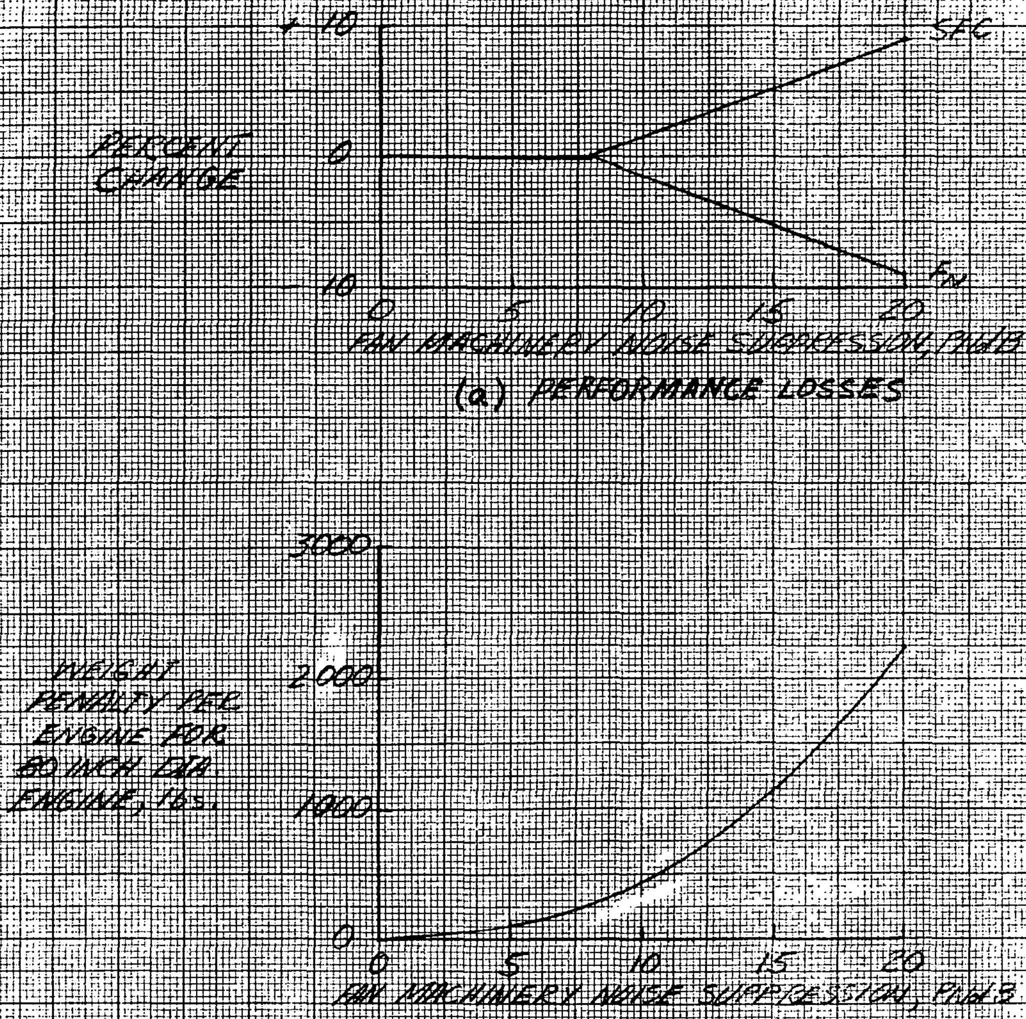


FIGURE 8. - THRUST, SFC, AND WEIGHT PENALTIES VERSUS AMOUNT OF FAN MACHINERY NOISE SUPPRESSION, PNdB.

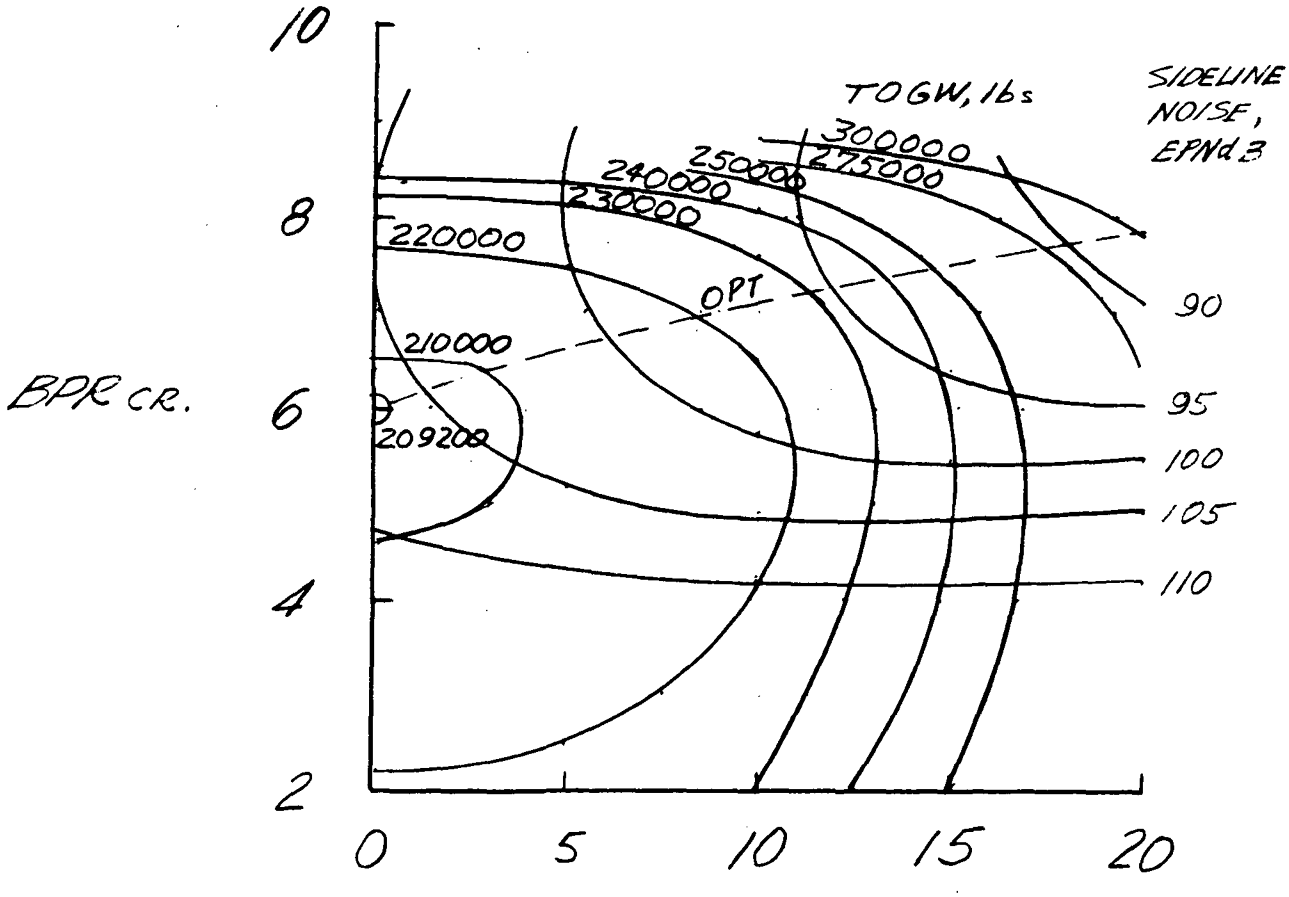


FIGURE 9. - "THUMBPRINT" PLOT SHOWING OPTIMUM CYCLE, OPTIMUM SUPPRESSION, AND MINIMUM TOGW FOR ANY SIDELINE NOISE LEVEL

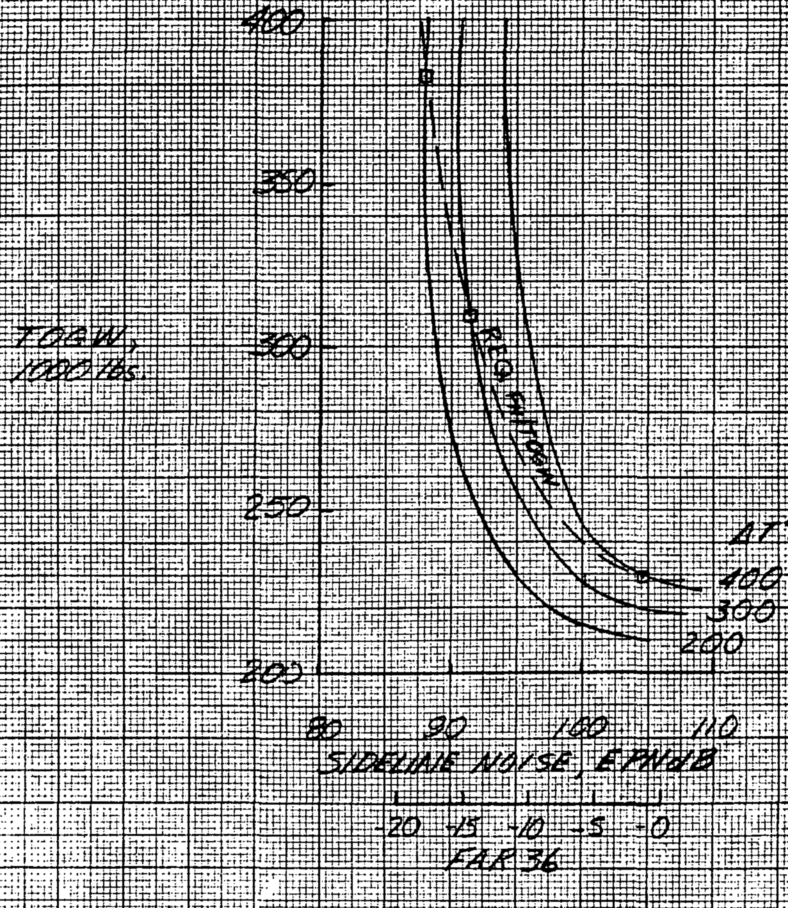


FIGURE 10. - TOGW VERSUS SIDELINE NOISE FOR THREE LEVELS OF CRUISE TA. OPTIMUM IS DEFINED BY REQUIRED TAKEOFF THRUST TO WEIGHT RATIO. $EPR_{cr} = 1.90$.

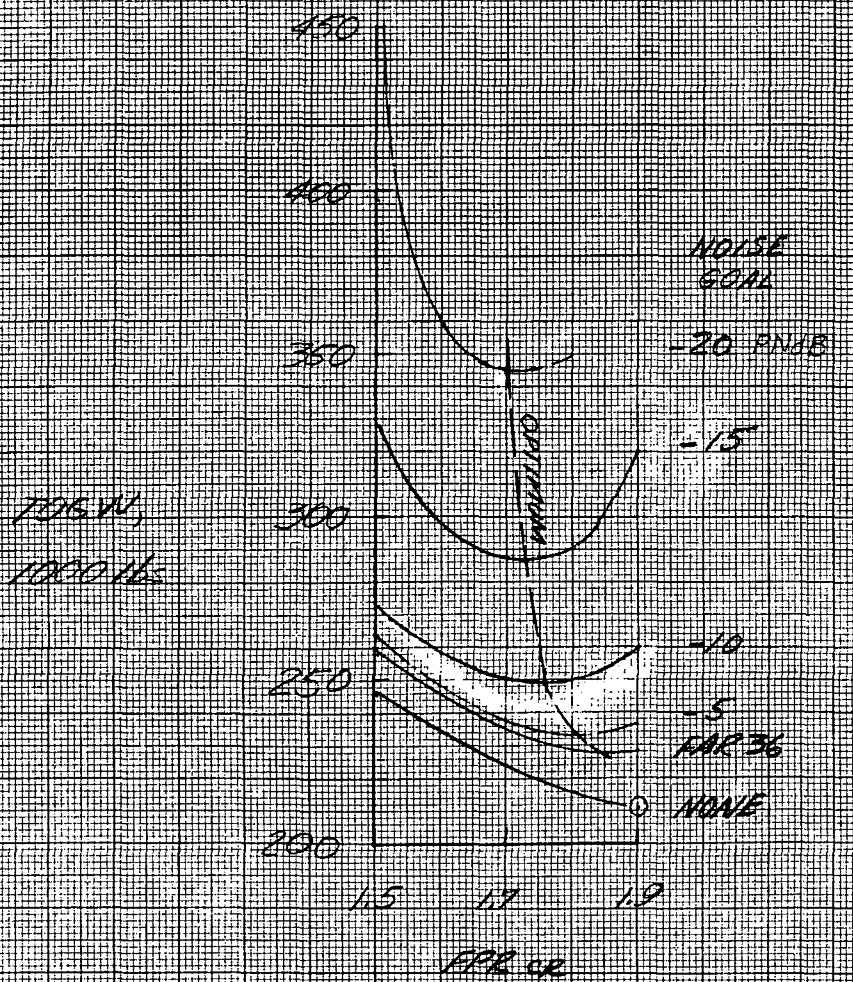
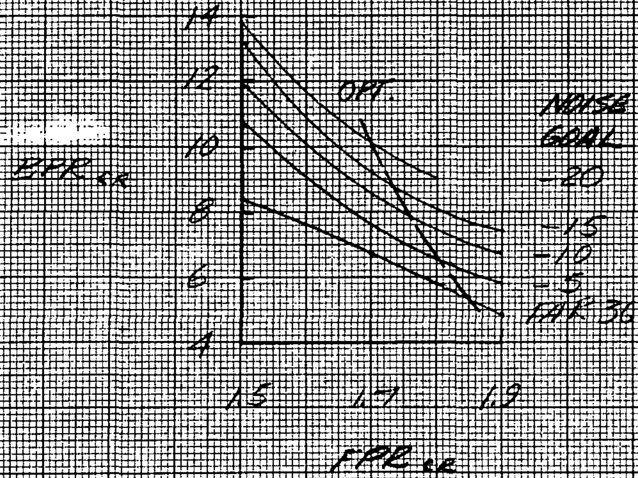
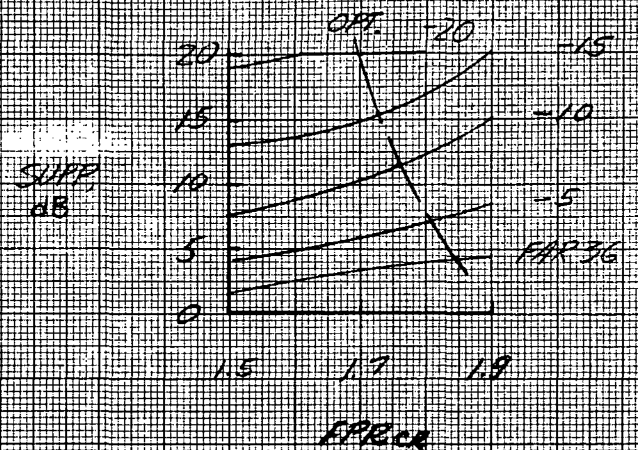


FIGURE 11. OPTIMUM TOGW VERSUS FPR CR FOR SEVERAL NOISE GOALS.

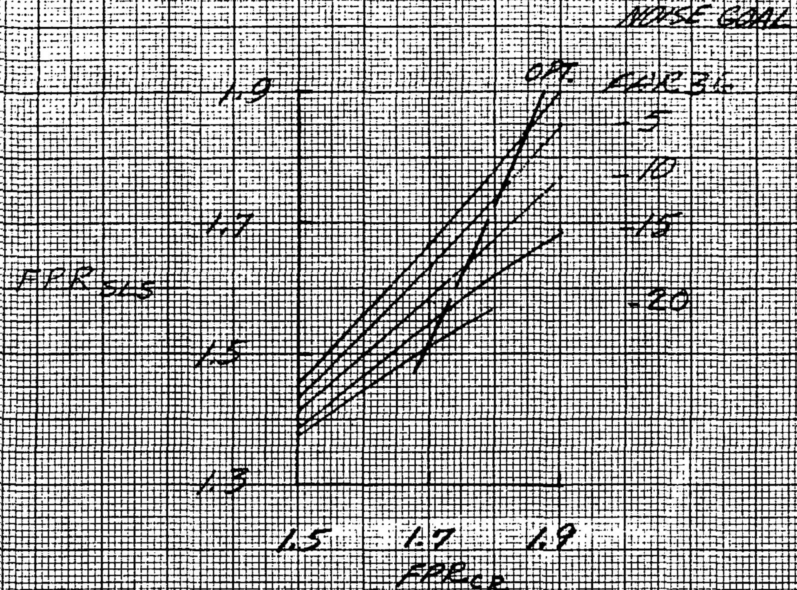


(a) OPTIMUM BPR

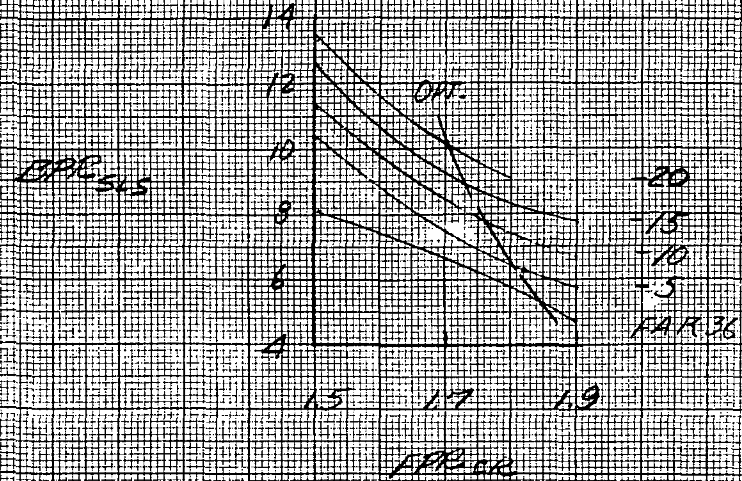


(b) OPTIMUM SUPPRESSION

FIGURE 12.- OPTIMUM CYCLE PARAMETERS AT VARIOUS NOISE GOALS

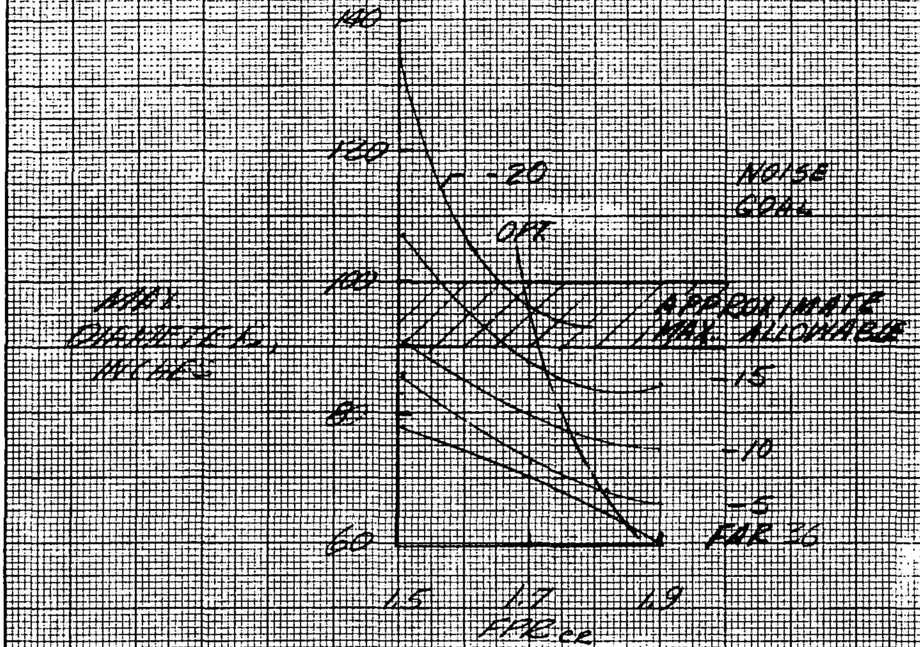


(c) OPTIMUM SLS FPR

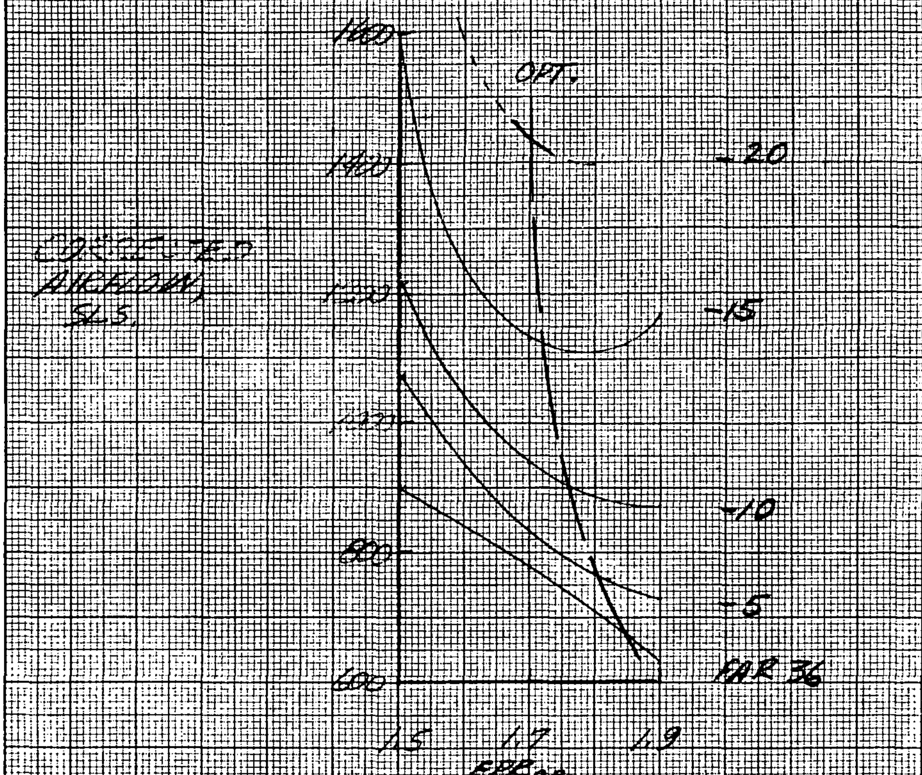


(d.) OPTIMUM SLS BPR

FIGURE 12.-CONTINUED.

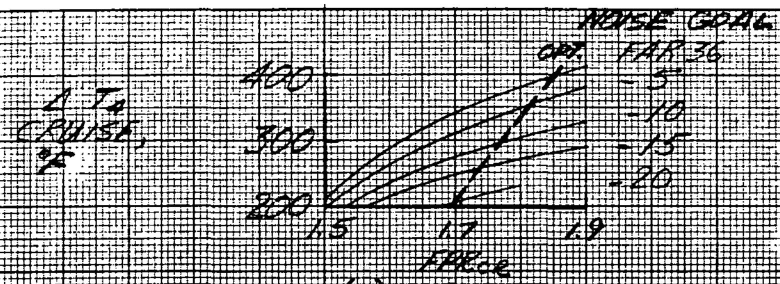


(e.) OPTIMUM DIAMETER

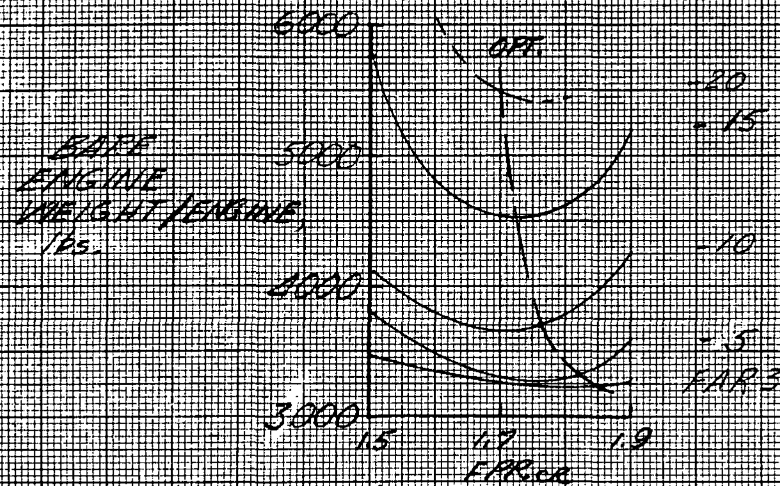


(f.) OPTIMUM CORRECTED Wa

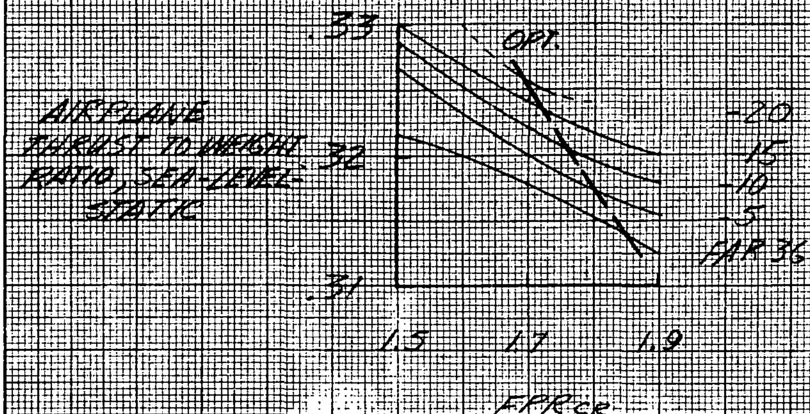
FIGURE-12 CONTINUED.



(g). OPTIMUM $T_{4\text{-}CR}$



(h) OPTIMUM ENGINE WEIGHT



(i)

FIGURE-12 CONCLUDED

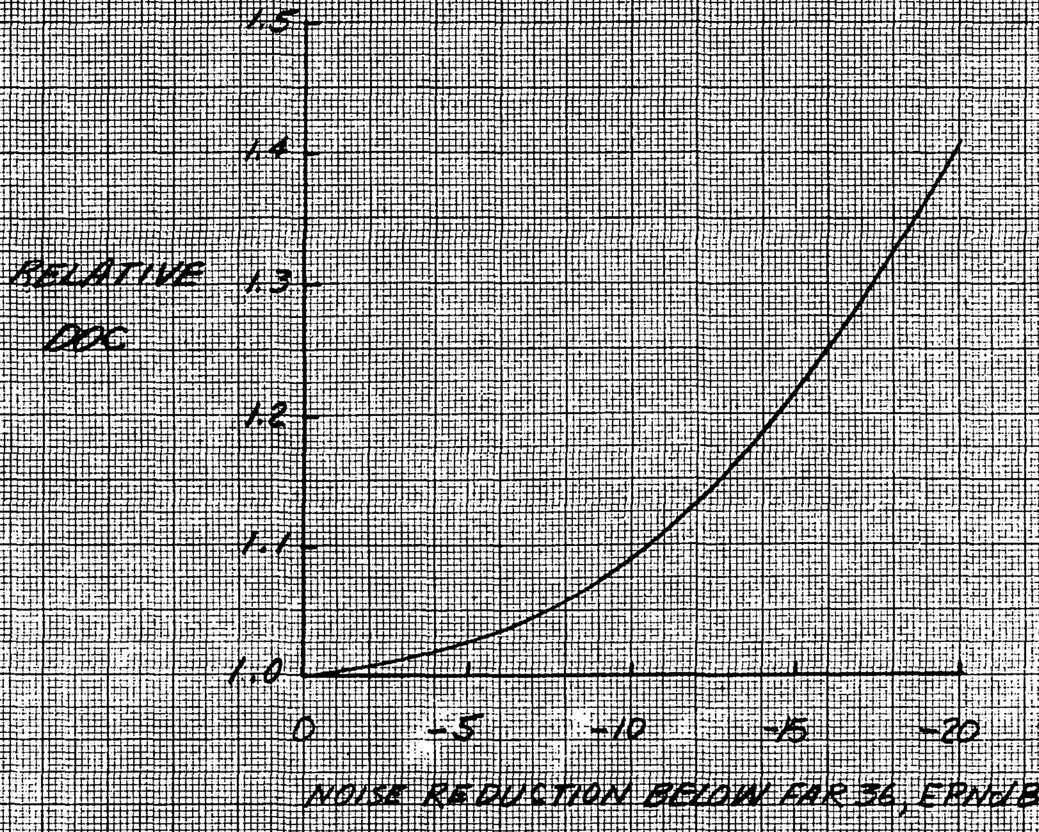


FIGURE 13.– RELATIVE DOC VERSUS NOISE LEVEL FOR THE OPTIMUM ENGINES. DESIGN MACH, 0.85; PAYLOAD, 200 PASSENGERS; RANGE, 3000 N.M.

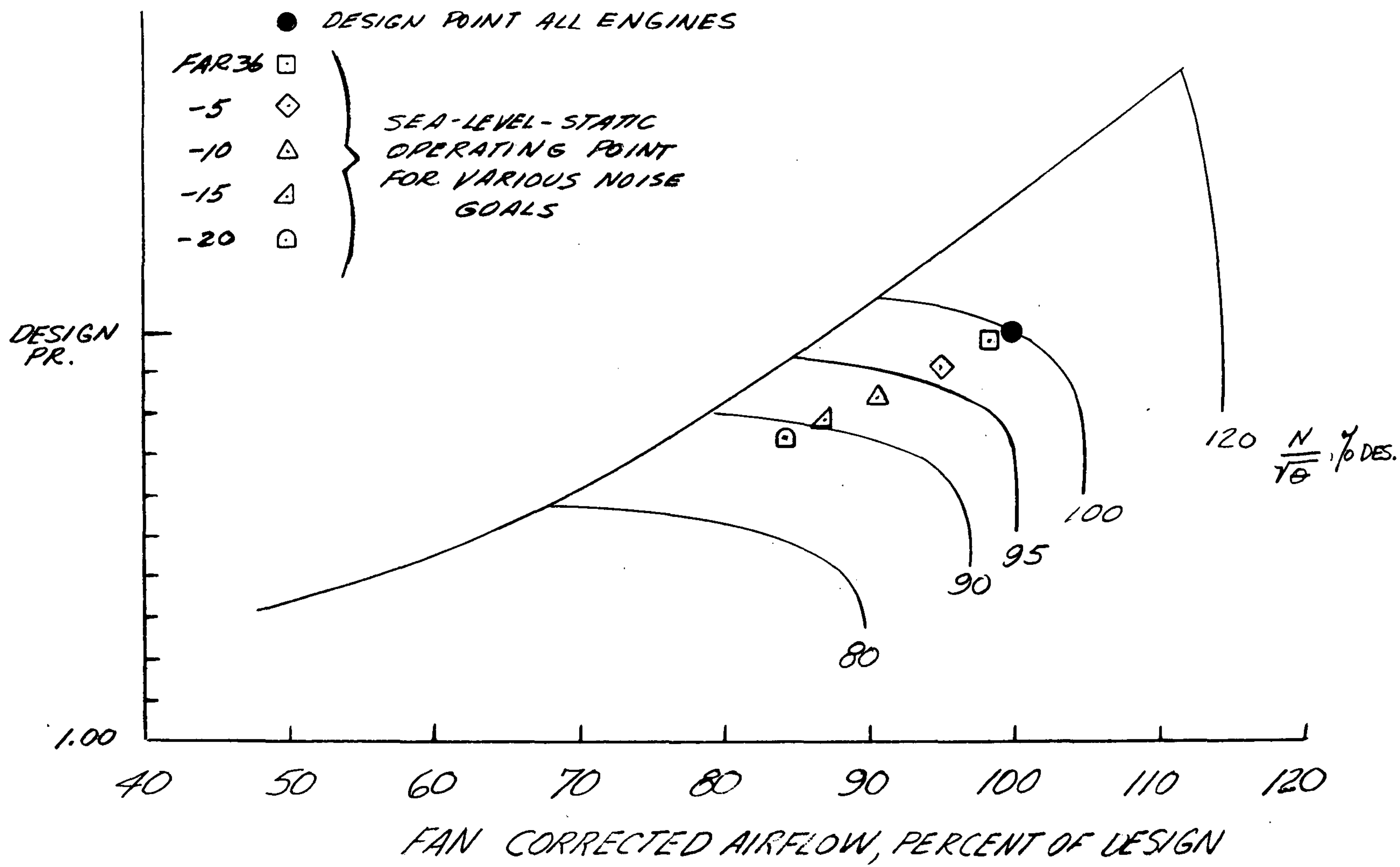


FIGURE 14. TYPICAL FAN MAP SHOWING RELATIVE POSITION OF DESIGN POINT AND SEA-LEVEL-STATIC OPERATING POINT FOR THE OPTIMUM ENGINE AT EACH NOISE GOAL.